Design of the Boeing 777 Electric System

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ABSTRACT

The electric power system chosen for the Boeing 777 is an example of the advances seen in response to market demands for superior performance and reliability. The system is being designed to take advantage of technologically-proven concepts, as well as new concepts to provide a fully automated state-of-the-art system. The system is comprised of two independent electrical systems, namely the main and backup. The main electric system includes two engine-driven integrated drive generators, a generator driven by the auxiliary power unit, three generator control units, and a bus power control unit. The backup electric system includes two engine-driven generators and one integrated converter/control unit to provide the redundancy of electrical sources equivalent to a three-engine airplane. Automation of the system is performed by the state-of-the-art, microprocessor-based control units. These units perform system control, protection, and built-in-test functions.

Each control unit has redundant two-way communication through a newly developed ARINC 629 communication bus. In addition to providing monitoring and built-in-test information to the aircraft information management system computer. the control units use this communication bus to communicate among themselves to provide many control and protection functions. By using this communication bus, the number of discrete wires previously required for similar systems has been significantly reduced, thereby allowing considerable reduction of the interface circuits and reduction in weight.

MAIN SYSTEM DESCRIPTION

The Boeing 777 is a large twin-engine jet transport designed for regional and longer range operations. There are two separate electric generating systems[1], a main system and a backup system (Figure 1). Both systems have a generator on each of the propulsion engines. In addition, the main system has a third generator on the auxiliary power unit (APU). The main electric generating system is the normal in-flight source of electric power. The generators in the main system are 3-phase, 115-Vac, line-to-neutral, constant-speed, 400-Hz machines. Each engine-driven generator is integrated with a constant speed drive, which together are called an integrated drive generator (IDG). On the APU, which operates at constant speed, only the generator portion is installed. The electrical loads are

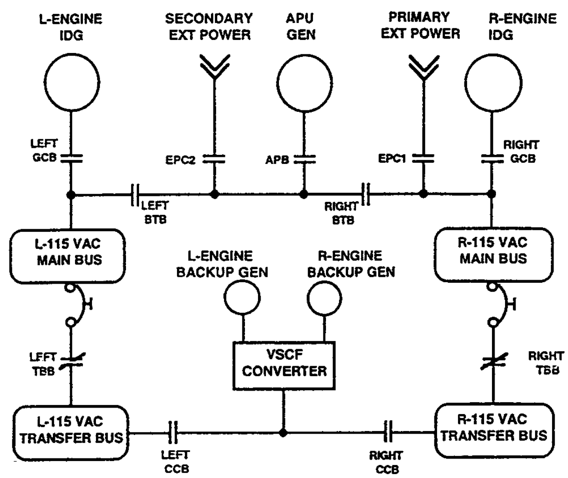

Fig. 1. Main and AC Backup Power

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[1] There is also an emergency generator driven by a ram air turbine, which is not covered in this paper.

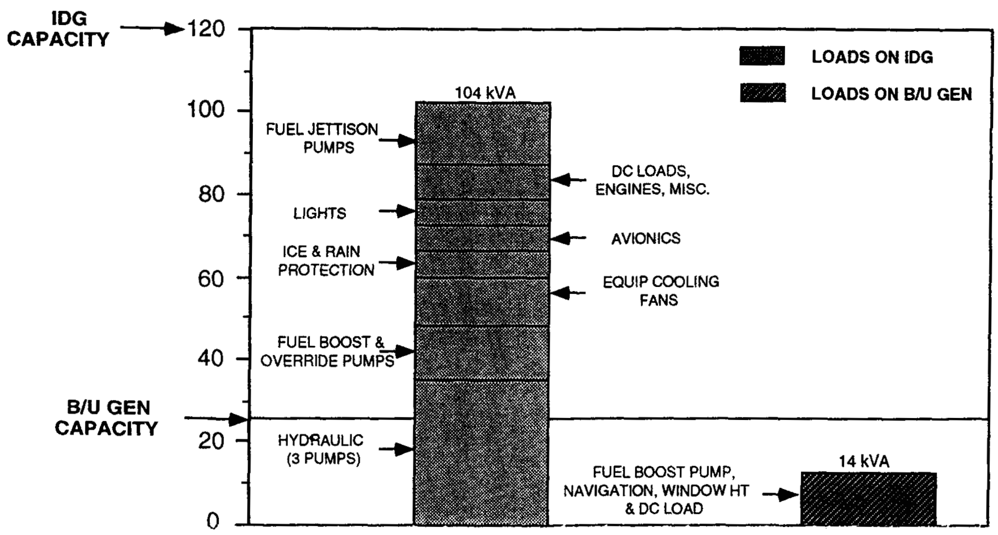

Fig. 2. Electric Loading With One Engine Out

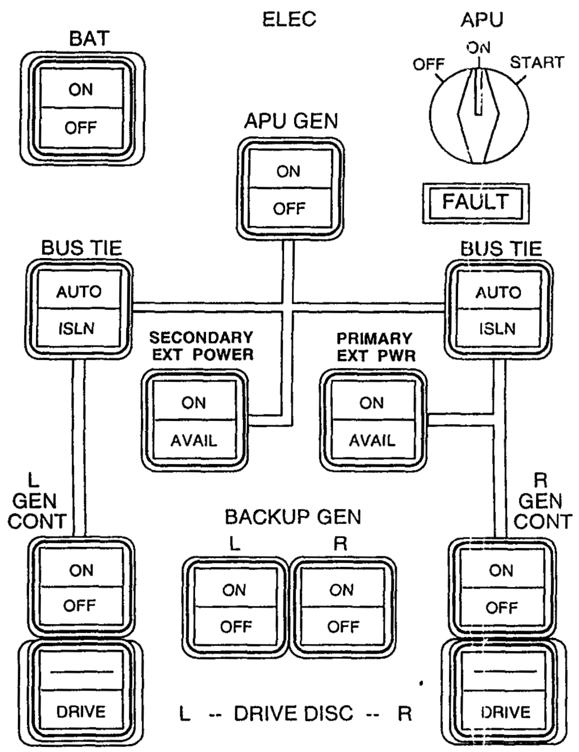

Fig. 3. Flight Deck Control Panel, Electric Power System

distributed from left and right main buses. Each of the three main generators can serve one or both of the two main buses.

The IDG on each engine serve its respective main bus through a generator circuit breaker. The two main buses can be connected through the bus tie breakers (BTBs). For loss of one IDG, the BTBs automatically close (connect), powering both main buses from a single IDG. Automatic load shedding is provided to prevent overloading the IDG under single-generator operation. The IDGs are rated at 120-kVA, which is sufficient to power all essential services during single-generator operation (Figure 2).

The third main generator, which is driven by the in-flight operable APU, is also rated at 120-kVA. This generator is connected between the BTBs through the auxiliary power breaker (APB). With an IDG inoperative, the APU generator can supply the respective main bus through the APB and BTB, but remains isolated from the other IDG. The airplane can be dispatched with one IDG inoperative by using the APU generator. Conversely, the system is designed to permit dispatch with the APU inoperative, if both IDGs are operating. For an in-flight failure of an IDG, the APU may be started to replace the inoperative IDG, but is not required. For single main generator operation, both main buses remain powered, and all essential electrical services are provided. For ground operation, external power can be connected to both 115-Vac main buses through an external power receptacle.

MAIN SYSTEM FLIGHT DECK CONTROLS AND INDICATION

Except for selection of external power, system operation is fully automatic. The flight deck control panel (Figure 3) has a generator control switch for each main generator. This switch normally remains in the ON position at all times. Operating the switch to OFF with the generator running will shut off the generator by opening its generator circuit breaker (GCB or APB) and generator control relay. In the event of a generator trip, the generator may be restored to the bus (if the cause of the trip is no longer present) by cycling the switch to OFF, then to the ON position. Bus tie switches control the BTBs and normally remain in the AUTO position. When this switch is

operated to the ISLN (isolation) position, the BTB is forced to open (isolate). This switch is primarily for maintenance and is not required to be operated in flight.

MAIN SYSTEM FAULT PROTECTION

Protection for the generator electrical feeder conductors between the generator and the generator circuit breaker[2] or auxiliary generator breaker is provided by differential current sensing. Current transformers in the generator and at the GCB or the APB compare the electrical current at both ends of the circuit and rapidly interrupt the circuit for a current difference exceeding approximately 50 and 75 A, respectively. Fault protection for the 115-Vac main bus and for the connection between the bus tie breakers is provided by unbalanced current sensing.

BACKUP ELECTRIC SYSTEM DESCRIPTION

The system has a backup electric generating system that operates independently of the main electric system. The purpose of the backup electrical system is to provide the equivalent redundancy of electrical sources as on a three-engine jet transport, considering failure of the main system. The backup system consists of one 20-kVA, variable-frequency generator on each engine, directly connected to the engine gearbox with no speed conversion.[3] The electrical output of the backup generators connects directly to a solid state variable-speed constant-frequency (VSCF) converter, which converts the power to a constant 400 Hz. Left and right 3-phase, 115-Vac transfer buses can be supplied from either their respective 115-Vac main bus or the VSCF converter.

The backup system will power either one or both 115-Vac transfer buses under the following conditions:

- During engine start, the backup system performs an automatic self-test by powering its respective transfer bus for approximately 15 sec. This is accomplished with a no-break power transfer.
- During Category IIIb autoland, the backup system will normally power the right 115-Vac transfer bus. This is accomplished with a no-break power transfer.
- One transfer bus is powered by the backup system during single main generator operation. It will power the transfer bus on the side of the inoperative IDG, except when the APU generator is supplying that transfer bus.
- For an open phase from the 115-Vac main bus, the backup system will power the respective 115-Vac transfer bus.
- For a main bus fault that deenergizes the 115-Vac main bus, the backup system will power the respective 115-Vac transfer bus.
- For loss of all main generators, except due to loss of both engines, the backup system will power both 115-Vac transfer buses.

[2] Referring to the electrical contractor in this paper as "breakers," i.e., circuit breakers, means that they provide fault protection and are rated to interrupt the maximum fault current.

[3] The backup generator also contains two independent permanent magnet generators that power the airplane flight control system. This paper does not cover the flight control portion of the electric power system.

BACKUP SYSTEM FLIGHT DECK CONTROLS AND INDICATION

Operation of the backup electrical system is fully automatic. No load monitoring or load shedding is required. There is a generator control switch for each backup generator. This switch normally remains in the ON position.

NO-BREAK POWER TRANSFER

Both the main and backup electrical systems are designed to perform no-break power transfers. Power transfers either to or from an IDG are done by speed trimming the governor in the IDG. With the airplane powered from external power, on engine start, the first IDG synchronizes with the external power frequency and closes its GCB when the voltage waveforms are in phase synchronization. The external power contactor then opens to complete the power transfer. The time the sources are in parallel kept to 50 ms maximum. Thus on transfer from external power to IDG power, both the left and right buses are transferred to the first IDG. No crew action is required.

When the airplane is powered from the APU generator, starting an engine transfers only the bus on the respective side. The other bus remains connected to the APU generator until its engine starts. No transfer occurs unless the IDG reaches a power ready condition, i.e., voltage and frequency are within acceptable limits. This feature is aimed at requiring no additional crew action if the airplane is being dispatched with an IDG inoperative. Again, both power transfers are no-break, with the IDG doing the synchronizing. Transferring from IDG power to external power requires operation of the external power switch. Operation of the external power switch (momentary push) initiates the synchronization by the IDG-Transferring from IDG power to APU power at the end of a flight is initiated by the engine fuel cutoff switch.

ADDITIONAL ELECTRIC SERVICES FOR EXTENDED TWIN OPERATIONS

The backup electrical power system was designed to permit extended overwater operations with the APU inoperative. The Boeing 767 had a 5-kVA hydraulic-driven generator for this purpose. This provided the following minimum get-home electric services:

1. Captain's instruments, navigation, and engine instruments
2. Engine ignition, starting, and thrust reverse
3. Flight deck, passenger cabin, and lavatory lighting
4. Fire detection and protection
5. Cabin pressure, environmental system, and equipment cooling
6. VHF and HF communications, interphone, and passenger address
7. Oxygen system
8. Wing and engine inlet antiice
9. Pitot heat, angle of attack probe heat and engine probe heat

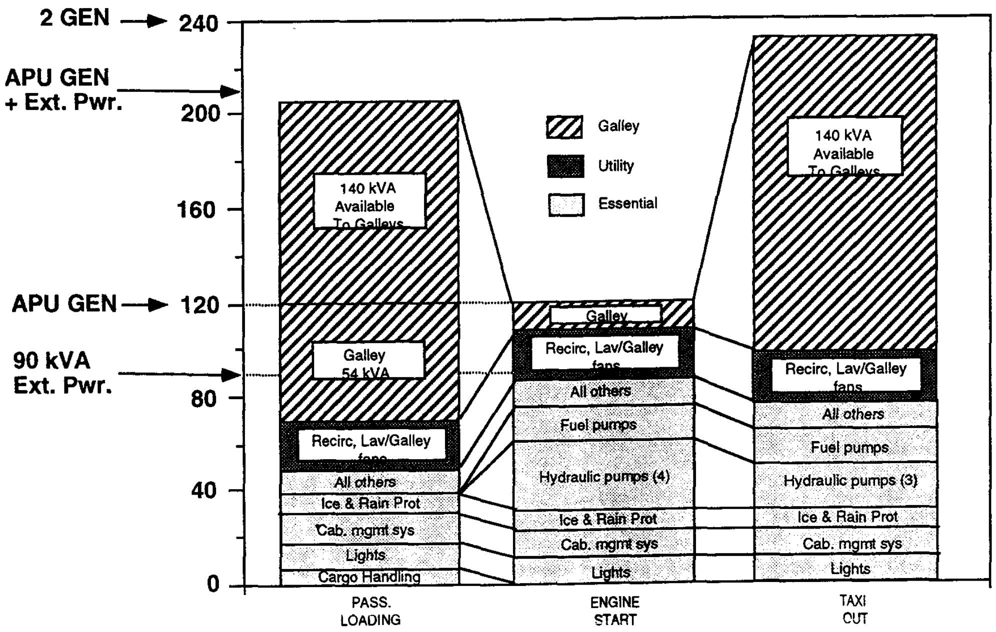

Fig. 4. Ground Electric Loads

10. Antiskid system
11. Stall warning
12. APU start
13. Fuel crossfeed
14. Cargo heat control
15. Rudder trim
16. Attitude Control System transponder
17. Flight management computer system (partial)

The 777 backup electrical is functionally the equivalent of the 767 hydraulic-driven generator, but with substantially more electrical capacity. In addition to the same services as provided by the 767 hydraulic-driven generator, the 777 backup power system also provides the following:

1. One fuel boost pump in each main fuel tank
2. Captain's No. 1 window heat
3. First Officer's flight instruments
4. Flight management computing system (full function)
5. Lavatory controls
6. Autopilot flight director system
7. Landing lights, wing tip lights, and strobe lights
8. Additional passenger cabin lighting

GROUND OPERATION

Ground power may be supplied from either the APU generator, from an external power source, or both. If the APU is inoperative or the APU is not used for economic reasons, ground power would be supplied from external services. Since 120-kVA ground power sources are not universally available, the airplane is designed to be supportable on external power from a single 90-kVA ground power source. To do this, automatic load shedding is installed so that a single 90-kVA external power source is not overloaded. With external power limited to 90-kVA, available galley service is limited to approximately 24-kVA while on external power. For engine start on external power, all galley services and utility services are automatically shed prior to engine start to insure the ability to start other heavy loads such as the electric driven hydraulic pumps. A second external power receptacle is installed so that full galley services can be supplied on the ground from two 90-kVA ground power sources when the APU is not in use.

With the APU operating, a full 120-kVA is available from the APU generator. This is sufficient electrical power to support all required electrical loads through engine start, with approximately 54-kVA available for galley services (Figure 4). This is about the same capacity for galley services on the ground as on the Boeing 747-400 and somewhat more than on the Boeing 767 (Figure 5), but which has proven to be sufficient, because full galley services are not normally required during this time. However, a new feature was added to the Boeing 777 to permit full galley services on the ground (140-kVA installed galley capacity). By connecting the primary external power to the right 115-Vac main bus, the APU generator can be used at the same time as external power, unlike the 767 which connects external power between the bus tie breakers. External power can be supplied to the right 115-Vac main bus while the APU supplies the left 115-Vac main bus. This was made possible at no weight or cost penalty by connecting the primary

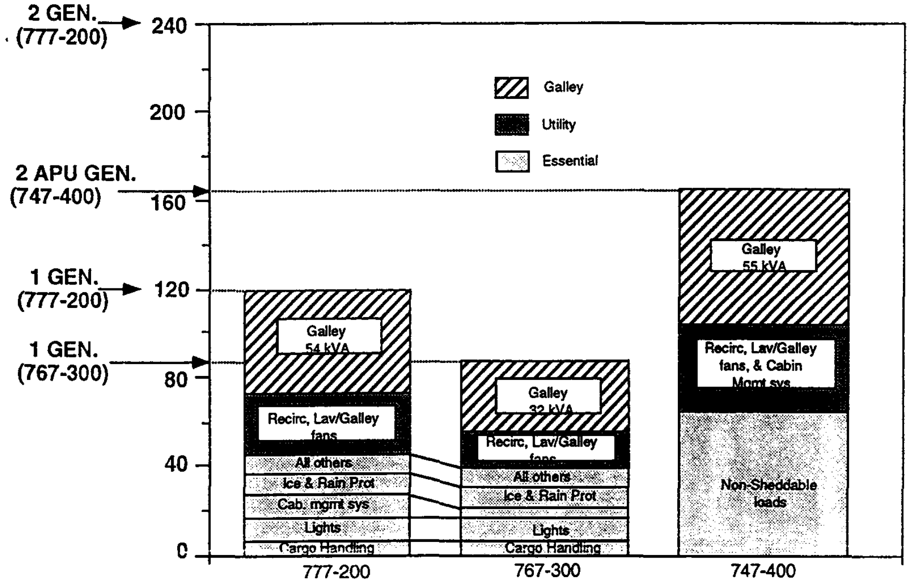

Fig. 5. Passenger Boarding, Electrical Load Comparison

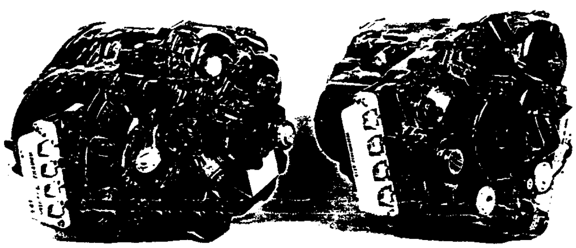

Fig. 6. 90-kVA IDG (left), 120-kVA IDG (right)

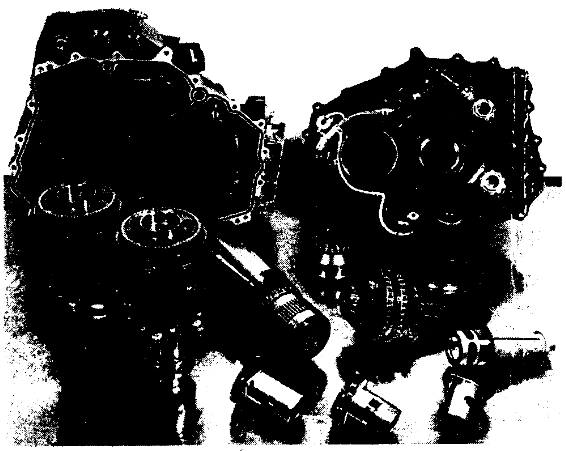

Fig. 7. IDG Assembly View

external power contactor to the right 115-Vac main bus. Thus when the cabin services requires full galleys on the ground before engine start, they can be provided by simultaneous use of the APU generator and external power.

AUTOMATIC LOAD SHEDDING AND RESTORATION

Automatic load shedding of nonessential electrical loads is implemented outside the main or backup electrical systems, as part of an integrated electric load management system. The electrical load management system will be built to accommodate variations between customers and, as such, can tailor the schedule of load shedding to suit the application and with better selectivity. Load shedding will be in finer steps than on the 767, and no loads will be shed unnecessarily. Services drawing only light loads will not be shed. Only sufficient loads will be shed to reach the rating of the source. Also, when a generator is restored, automatic load restoration will take place.

SIMPLIFICATION OF BUS FAULT PROTECTION

The Boeing 777 electrical power system and the 767 electrical power system are designed to protect the system against electrical faults (short circuits) or equipment failure that would lead to unsafe operating temperatures or further loss of services. The addition of unbalanced current protection to the Boeing 777 has allowed a simplification of the differential current protection scheme with a reduction in the quantity of current transformers.

EQUIPMENT DESCRIPTION

Integrated Drive Generator

The IDG is of 120-kVA load rating. The use of a 24,000-rpm,

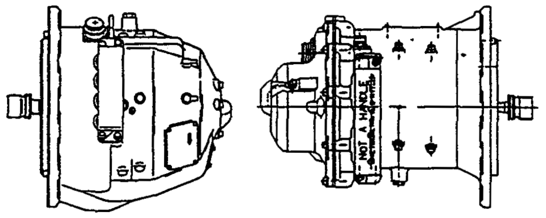

Fig. 8. 90-kVA Generator (left), 120-kVA Generator (right)

2-pole generator and other improved features accomplishes an IDG package that fits into the space on the engine pad previously occupied by a 90-kVA IDG. For comparison, the 90-kVA IDG presently used on both the 757 and 767 aircraft is shown (Figure 6) next to the 120-kVA IDG used on the 777. The IDG has the advantage of improved specific weight (pounds per kVA ratio) and better efficiency compared to the previous 90-kVA design. Several design features are included to accomplish remote indication for check out of the IDG without the need to gain physical access to the engine compartment. Parameters sensed include oil temperature and oil level.

The IDG is similar to those chosen for the MD-11 and the Airbus A-330 applications. A view of the IDG interior is shown in Figure 7. The established confidence in reliability achieved by selection of the hydromechanical IDG is enhanced by the experience which will have been accrued on the IDG of these applications. The incorporation of the two-pole generator has resulted in several gains; a reduction in generator weight and volume; improved generator efficiency, including reduced windage and rotor dra-glosses due to a "canned" rotor design; and back iron stator cooling.

The improved oil management system of the 120-kVA IDG provides the following benefits: less free oil, resulting in lower mechanical churning losses; improved mechanical efficiency of the hydraulic assemblies; improved attitude capability; and greater tolerance for overfill and low oil level operation.

Lessons learned from the 90-kVA IDG on the 757/767 airplane have been used to incorporate new features on the 120-kVA IDG, as described below:

Thermal Disconnect. The input disconnect is provided as a cost-of-ownership enhancement. The mechanism provides an electrically actuated input disconnect similar to that on the 90-kVA IDG which is initiated by switch actuation from the flight deck. A new feature of the mechanism senses internal IDG operating temperature and will automatically disconnect the IDG from the gearbox if that temperature exceeds a predetermined threshold. The device is triggered by a eutectic solder plug that is contained in the disconnect mechanism. Timely disconnect due to abnormally high operating temperature will significantly reduce subsequent IDG repair cost.

Case Venting. To achieve an extension of oil and filter life, a feature has been added into the IDG to purge the oil of moisture. Moisture has been the cause of acid formation, hydrolysis, and filter plugging. When not operating, the IDG case is sealed from the ambient air.

The purge system consists of four major parts: an air inlet check valve; an aspirator to pump air into the unit; an air-oil separator at the exhaust; and a valve to allow the air out during operation.

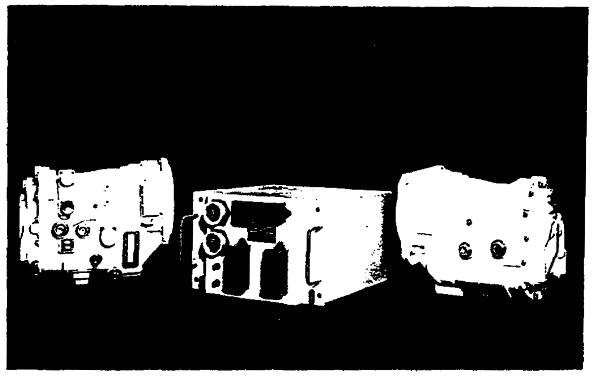

Fig. 9.

Magnetic Pickup (MPU) Deletion. A magnetic pickup had been planned, as in other IDG's, as a means of supplying a signal of engine speed as a part of the electrical load switching logic. The availability of signals from the engine through hardwire and ARINC 629 (e.g., fuel cutoff and engine speed) has made it possible to implement logic in the generator control unit (GCU) that performs a similar function as that of the MPU, thus allowing its deletion. This feature will enhance the reliability of the system since the MPU has historically been a source of nuisance trips for the IDG. Furthermore, the elimination of the MPU and associated circuitry further reduces the weight of the system.

APU Generator. A generator is supplied to fit to the APU. This generator is the same 120-kVA, oil-cooled generator as in the IDG, but arranged in a dedicated housing. This generator is of the highest technology currently available, with excellent weight efficiency, reliability, and maintainability characteristics. As pictured, (Figure 8), the volumes are nearly identical for the new 120-kVA and the previous 90-kVA units; but, as with the IDG comparison above, the 120-kVA APU generator also has a 33-percent increase in power output capability.

Control Units. State-of-the-art, microprocessor based GCU and bus power control unit (BPCU) are designed for safe and reliable operation while providing several new features to enhance ease of usage and maintainability. The units use the structured Ada high-level software language to provide control, protection, and built-in-test functions. Moreover, the software and the hardware are partitioned to maintain the integrity of these functions and to facilitate maintenance. The hardware is designed to withstand the new high-intensity radiated field and lightning level imposed by the Federal Aviation Administration.

Dual (redundant) ARINC 629 communication buses are provided in the GCU and BPCU. The ARINC 629 buses are used for communication between the control units and with other aircraft systems. Functions accomplished through ARINC 629 communication include system control and protection; monitoring and built-in-test equipment (BITE) information to the central aircraft information management system (AIMS) computer and real-time status of all main ac electrical power system control switches for display on the flight deck. The ARINC 629 buses can also be used for onboard software loading. This software loading capability simplifies the process of upgrading or modifying the software within the control units in that there is no need to remove the units from the airplane for software upgrading. Moreover, test software can also be downloaded to the control units in the shop to ease troubleshooting and shop test.

BITE. The electrical power system (EPS) for the Boeing 777 airplane will incorporate sophisticated BITE to aid maintenance crews in troubleshooting the aircraft by the provision of accurate fault reporting and data. The BITE system will monitor and verify the integrity of the EPS on the aircraft. The verification process will include protective trip isolation, continuous monitoring of system conditions, and initiated self-test modes of operation. The control units contain the intelligence to perform the fault detection, isolation, reporting, and storage of relevant fault information. Certain fault records are stored in nonvolatile memory (NVM). These records contain information as to the type of fault, the flight leg and flight phase in which the fault occurred, airplane identification, date, time, and the type of BITE operation that detected the fault. The NVM has the capability to store fault records up to 64 flight legs. The information stored in NVM is primarily for shop maintenance, but the data can be retrieved on the aircraft through the central maintenance computer system (CMCS), if desired.

The ARINC 629 system communication bus is the medium by which fault information is transmitted to the aircraft CMCS. It also transmits specific BITE commands from the CMCS to the EPS digital control units, which is useful in further isolation of a problem.

IDG Oil Level Sensing. A conventional sight glass indicator is provided on the 777 IDG. The sight glass indicator plate is referenced to an overflow standpipe inside the IDG, which establishes the proper oil level during servicing.

Additionally, a remote oil level sensor has been incorporated that will allow oil level checks to be accomplished without access to the IDG.

The device uses thermal dispersion sensors and operates on the principle that heat is generated in the resistive element of the sensor probe(s) by passing a constant current through the element. This heat is dissipated at a different rate depending on whether the element is above or below the static liquid level.

Voltage readings will determine which sensor, if any, is "wet." This will indicate whether the oil level is normal or otherwise. The appropriate indication will be forwarded to the AIMS readout.

BACKUP SYSTEM DESCRIPTION

VSCF System

Two variable-speed generators, one for each engine, supply a 20-kVA converter. Either generator is selected to power the converter, leaving the second generator in a standby mode. If given any generator input speed between 13,484 and 26,763 rpm, the system will provide a constant 400-Hz, 115-Vac line-to-neutral output (Figure 9).

Variable Speed Generators

Each 8-pole generator has an integral oil cooling system contained within a single structural generator housing. This cooling method is identical to the main system generators. Servicing check time is minimized using remote oil level condition sensors. In addition to the main generator output, there are three separate 3-phase permanent magnet generators (PMGs). One PMG output is used for converter control. The other PMGs provide fly-by-wire power requirements. Each PMG is electrically and magnetically isolated.

Converter

There are two distinctly separate sections within the converter. One performs the power conversion process and the other provides system control, protection, and communication. Power conversion is achieved by rectifying the variable-frequency input and switching the dc power in a bridge network to provide a 3-phase sinusoidal output. At the heart of the process are six power switches, two per phase, that use integrated gate bipolar transistors.

The controller provides conventional control and protection for system operation and a switch pattern select capability for the power switches. ARINC 629 and BIT functions are also performed in a method similar to that of the main channel. Forced air cooling is ducted from the aircraft environmental system and is supplemented by a standby fan powered from the converter output.

The converter has two voltage regulators. Each voltage regulator is dedicated to its respective generator. The selected generator's regulator maintains the converter output voltage at 115-V while the second regulator is run in a standby mode. A measure of system redundancy is provided by this dual power source capability.

List of Acronyms

AIMS	airplane information management system
APB	auxiliary power breaker
APU	auxiliary power unit
ARINC	Aeronautical Radio Incorporated
AUTO	automatic
BITE	built-in-test equipment
BPCU	bus power control unit
BTB	bus tie breaker
CCB	converter circuit breaker

CMCS	central maintenance computer system
EICAS	engine indicating and crew alerting system
EPC	External Power Contactor
EPS	electric power system
GCB	generator circuit breaker
GCU	generator control unit
IDG	integrated drive generator
ISLN	isolation
NVM	nonvolatile memory
TBB	transfer bus breaker
VSCF	variable-speed constant-frequency
767	Boeing Model 767 commercial jet transport airplane
777	Boeing Model 777 commercial jet transport airplane